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Sub-Zero Temperature Behaviour of Cold-formed steel Members

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Abstract

Cold-formed steel (CFS) industry has opportunities to expand the use of CFS in sub-zero temperature environments, such as Arctic and Antarctic regions, large scale refrigeration facilities and off-shore structures. Although the behaviour of hot-rolled steel members in such environments has been investigated, limited studies are available for CFS members at sub-zero temperatures. Thus, tensile tests were conducted on low and high strength cold-rolled steel sheets to determine their mechanical properties in the temperature range of 20 to -70 ℃. Predictive equations were developed to determine the sub-zero temperature mechanical properties of CFS using their ambient temperature mechanical properties. Sub-zero temperature ductility of CFS was investigated against CFS design standards. Also, the issues of performing standard toughness tests on CFS due to dimensional limitations were identified. Moreover, CFS stub columns were tested at sub-zero temperatures to investigate their behaviour. Tests showed that there were no premature failures caused by brittle fracture, even after significant localised deformations during the post-ultimate phase. In all cases, the ultimate capacity increased considerably even at temperatures below -50 ℃, especially for low strength steel columns.

1. Introduction

The polar regions and high altitude mountains experience harsh cold climatic conditions. Latip et al. [1] reported that -87.2 ℃ (Vostok Station in East Antarctica) was the lowest recorded temperature on the earth. It was recorded in the South Pole while -68 ℃ was the lowest temperature recorded in the Arctic region (the North Pole). People have been living in the Arctic Circle, which includes part of Russia, USA, Canada, Norway and Greenland, for thousands of years despite the sub-zero temperature environment. Although Antarctica does not contain permanent habitats, many researchers and tourists visit the South Pole. On the other hand, North and South poles are rich in natural resources. Increased oil and gas explorations in North Pole have attracted people to move closer to the region. However, people living in the polar regions or high altitude mountains do not have good infrastructure facilities enjoyed by others due to the difficulties in using conventional building materials such as hot-rolled steel and concrete. Shorter day time, transportation difficulties, freezing temperatures, and knowledge gaps on the performance and design of building materials at sub-zero temperatures are some of the construction difficulties in the polar regions.

Although timber is one of the popular materials in the polar regions, it is heavier, less durable and vulnerable in fire compared to cold-formed steel (CFS). Pre-assembled Light Gauge Steel Frame (LSF) wall and floor systems made of cold-formed steel members are suitable for cold-region construction as they reduce the construction and transportation costs. Also, the knowledge enhancement in cold-formed steel design and construction at ambient and elevated temperatures in recent decades is an added advantage. However, limited effort has been taken in studying the sub-zero temperature behaviour of CFS members so far. This means that although CFS construction is now widely used in residential, commercial and industrial buildings around the world, it may not be used in the buildings in cold-regions. Polyzois et al. [2] investigated the compression capacity of cold-formed steel angles used in lattice towers in the temperature range of -45 to 25 ℃. Abdel-Rahim and Polyzois [3] investigated the mechanical properties of cold-formed steel sections, which are also used in lattice towers, in the range of ambient temperature to -50 ℃. They concluded that low temperatures significantly affect the yield strength, ultimate strength and maximum percentage of elongation of steels. However, the thickness of their sections is higher than those used in LSF walls and floors. Yan et al. [4] investigated the compression capacities of CFS hollow sections in the temperature range of -80 to 20 ℃. To date, there are no studies on the sub-zero temperature mechanical properties of thin cold-rolled steel sheets or cold-formed steel members.

On the other hand, many researchers have investigated the sub-zero temperature mechanical properties of other metals. Levings and Sritharan [5], Yan et al. [6], Yan and Xie

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[7] and Azhari et al. [8] investigated the sub-zero temperature mechanical properties of ASTM A706 Grade 420 steel reinforcement, normal and high strength hot-rolled steel, various grades of reinforcement steel and ultrahigh strength steel, respectively. Levings and Sritharan [5] showed that ASTM A706 Grade 420 steel reinforcement experienced 5.1% and 6.3% increment in yield and ultimate strengths, respectively at -40 ℃. Similarly, Yan et al. [6] reported that yield strength, Young's modulus, ultimate strength and fracture strain increased as the temperature reduced. They observed yield strength increments of 13%, 21% and 7% at -80 ℃ for 4 mm mild steel, 12 mm mild steel and high strength steel, respectively. However, Yan and Xie [7] found that ductility of reinforcement steel reduced as temperature decreased while yield and ultimate strengths increased. Azhari et al. [8] also found that yield and ultimate strengths of ultra-high strength steel increased with reducing temperatures below zero while ductility reduced. Hence, it is important that sub-zero temperature mechanical properties of cold-rolled steels are investigated as a function of reducing temperature to sub-zero levels.

An experimental study was undertaken in this study to investigate the sub-zero temperature mechanical properties of cold-rolled steel sheets and the results were used to propose new predictive equations and suitable stress-strain models. This study was then extended to investiagte the sub-zero temperature local buckling and yield capacities of cold-formed steel columns (lipped-channel sections) subject to static compression loads. This paper presents the details of this experimental study and its results.

2. Experimental study

2.1 Test specimens and test method

A series of uniaxial tensile tests was conducted to determine the sub-zero temperature mechanical properties of low (G300) and high (G550) strength cold-rolled steel sheets. The base metal thicknesses of chosen steels are 0.55 mm, 0.80 mm and 1.0 mm for G300 steels and 0.55 mm, 0.75 mm and 0.95 mm for G550 steels. Similarly, a series of uniaxial compression tests was conducted to determine the local buckling and yield capacities of short CFS lipped channel section (LCS) columns made of G550 and G300 steels at sub-zero temperatures. A group of 0.55 mm G550 and G300 CFS-LCS columns subject to local buckling and another group of 0.8 mm G300 CFS-LCS columns subject to yielding failure were tested. The tension and compression tests were conducted in the temperature range of +20 to -70 ℃ under steady state conditions.

Tensile coupons were extracted in the longitudinal direction of cold-rolled steel sheets and prepared as per the dimensions given in AS 1391 [9] (Figure 1). The ambient temperature tensile testing standard of metals was used since there is no Australian Standard for sub-zero temperature tensile testing of metals. However, the dimensions were verified using the International Standard for sub-zero temperature tensile tests of metals, BS EN ISO 6892-3 [10]. Tensile coupons were extracted using the water jet cutting method as recommended by Imran et al. [11]. Five mm strain gauges with an operating temperature range of -196 to 150 ℃ were attached to both sides of the coupons (Figure 1). The cross-sectional dimensions and the length of the LCS columns were then chosen based on the elastic local buckling analyses undertaken using CUFSM. The centerline dimensions of the 120 mm (greater than three times half wave length) CFS columns are given in Figure 2.

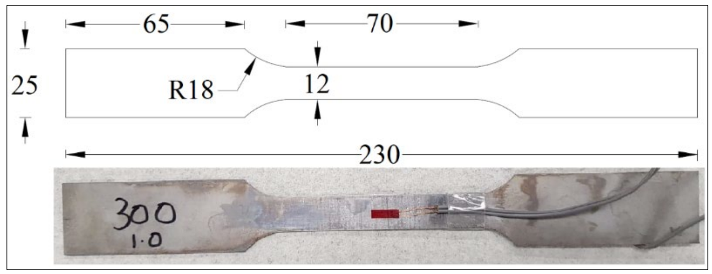


Figure 1: Dimensions of tensile coupons.

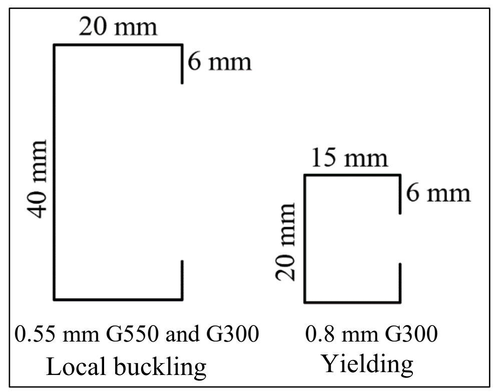


Figure 2: Centreline dimensions of tested lipped channel sections.

Two end plates (top and bottom) were prepared with mechanical fixing arrangements to provide fixed-end condition for column tests as shown in Figure 3. Although the influence of end support conditions on local buckling and yielding failures is small, end plates help to avoid eccentric loading. Four cleats and a centre plate were located at each end to avoid any eccentric loading.

The maximum sub-zero temperature selected in this study was -70 ℃ since the maximum measured temperature in the arctic region, where people live, is -68 ℃. Also, the temperature of steel members will be less than the outside temperature as they are protected by boards and insulation materials. The tensile coupons and the columns were tested at 20 ℃, -10 ℃, -30 ℃, -50 ℃ and -70 ℃ under steady-state conditions. Two tensile coupons and columns were tested at each temperature.

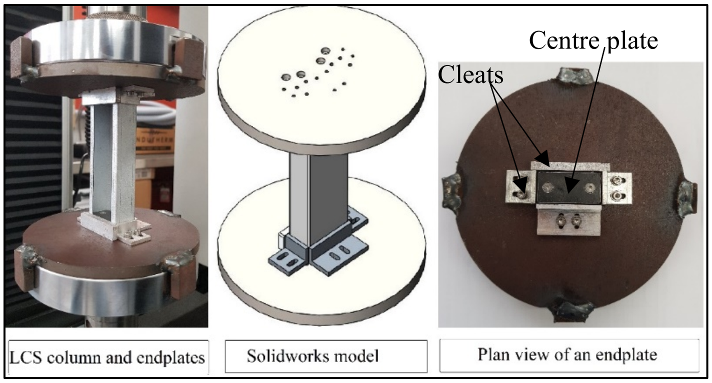


Figure 3: End plates used in the column tests.

2.2 Test set-up and procedure

The sub-zero temperature tensile coupon test facility at QUT was used to test the coupons at both ambient and sub-zero temperatures. Figure 4 shows the sub-zero temperature tensile test set-up. It consisted of a 30 kN Instron testing machine, an environmental chamber with a Eurotherm control unit and a liquid nitrogen cylinder. Liquid nitrogen was used as the cryogen in this study. The environmental chamber has an operating temperature range of -100 °C to 350 °C. The Instron testing machine was connected to a Bluehill universal software system for data acquisition purposes and to control the loading process. A laptop with LabVIEW 2017 software was used to record the measured strains from the strain gauges and temperatures from the thermocouples attached to the tensile coupons.

Thermocouples were also attached to the tensile coupon (Figure 5). After the initial set-up, the tensile coupon was loaded to 50% of the expected yield load using a displacement control method (1mm/min) [11] and then unloaded. These loading and unloading processes were repeated three times for each coupon. The Young's modulus was calculated for each loading process and compared with the nominal value of 200 GPa. This procedure was used to ensure the vertical and horizontal alignments of the coupon. The sub-zero temperature Young's modulus increment factors were calculated using the ambient temperature Young's modulus obtained from the preloading process and the corresponding sub-zero temperature Young's modulus as recommended in [11].

Similar test set-up and method was used for column tests with some modified arrangements as shown in Figure 6. The test column fixed to the two end plates was placed between the loading plate (top) and the supporting plate (bottom) of Instron testing machine as shown in Figure 6. Thermocouples were then attached to the test.

The target temperature of the environmental chamber was set using the Eurotherm control unit. The target temperature was set lower than the test temperature as there was a temperature difference between the in-built thermocouple attached to the environmental chamber wall and the thermocouples attached to the tensile coupon due to heat loss. Liquid nitrogen was then released into the chamber and distributed evenly through a fan attached to the chamber. The target temperature was adjusted based on the readings of the thermocouples attached to the coupon or column. The tensile coupon was subject to contraction as the coupon temperature decreased. The coupon and column were kept at the target test temperature for about 15 min to ensure a uniform temperature across the cross-section. Finally, relevant load (tension for coupon and compression for column) was applied using a displacement control method (1 mm/min) until failure.

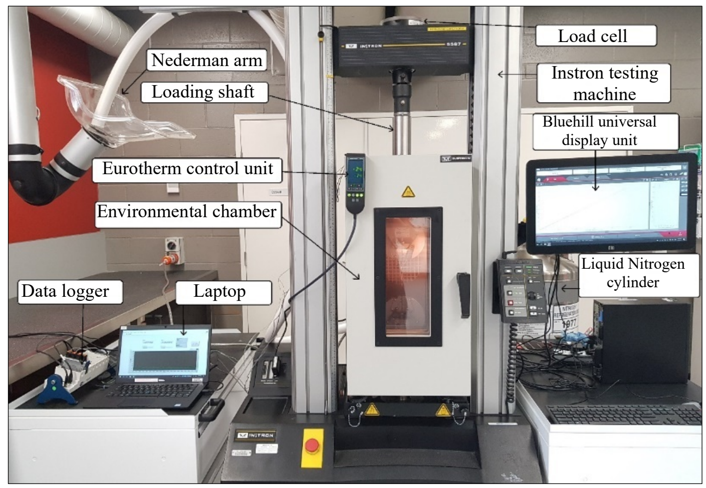


Figure 4: Sub-zero and ambient temperature tensile test set-up.

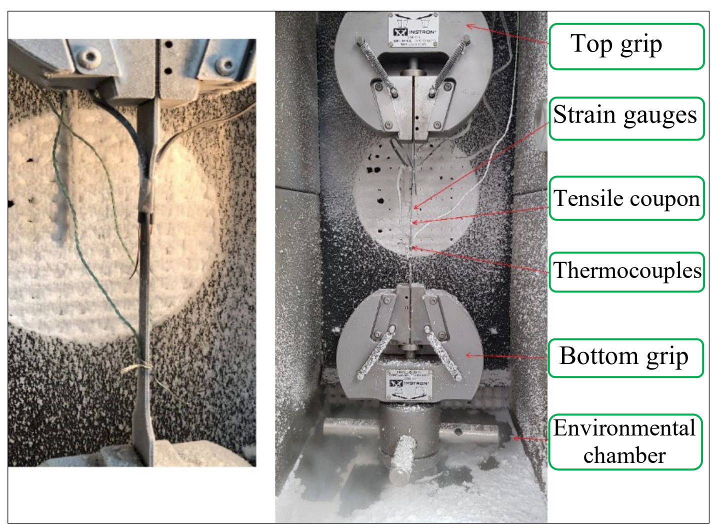


Figure 5: Arrangement of strain gauges and thermocouples.

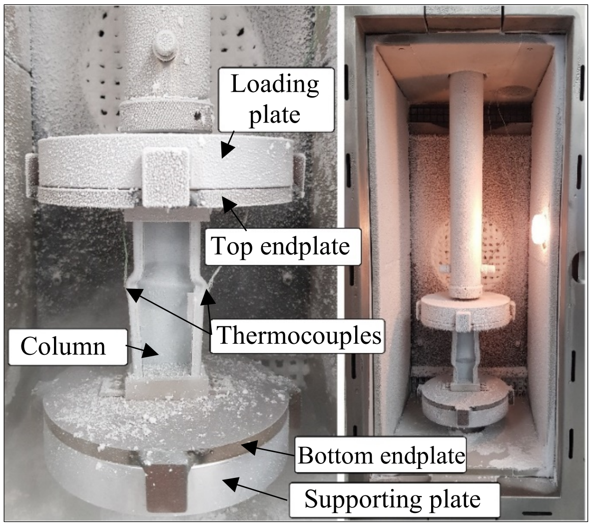
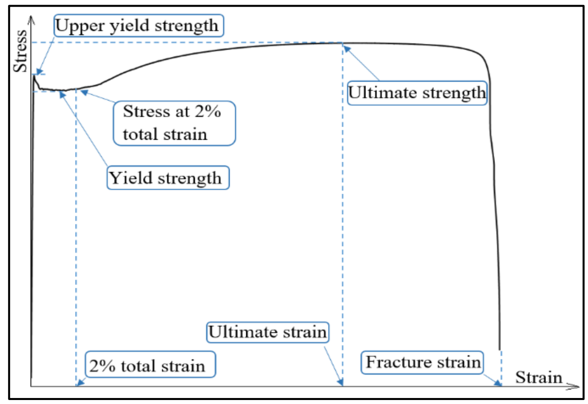


Figure 6: Test column inside the environmental chamber.

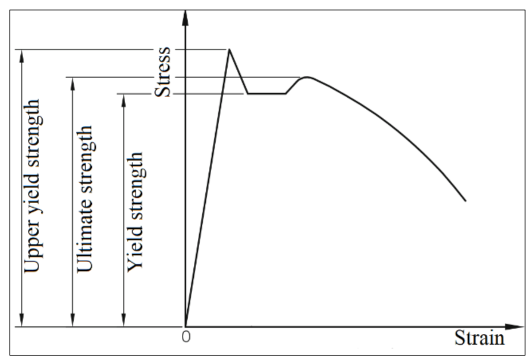
3. Sub-zero and ambient temperature mechanical properties and predictive equations

This section presents the measured sub-zero temperature mechanical properties of six cold-rolled steel sheets (LSS G300 and HSS G550 steels with three thicknesses each) including their full engineering stress-strain curves. The ambient and sub-zero temperature mechanical properties such as yield strength (0.2% proof stress if the stress-strain curve exhibits gradual yielding), upper yield strength, Young's modulus, ultimate strength, ultimate strain and fracture strain were determined from the experimental stress-strain curves. The term yield strength is used in this paper instead of lower yield strength and 0.2% proof stress as AS/NZS 4600 [12] recognises them as the yield strength. These results showed that mechanical properties in general increased/improved with decreasing temperature. The average mechanical properties of cold-rolled steel sheets were then used to derive the predictive equations of sub-zero temperature mechanical property increment factors.

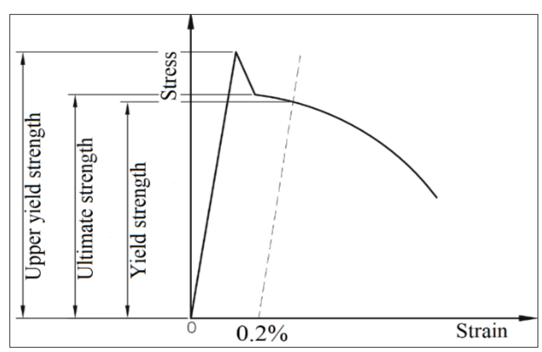
The stress-strain curves of 0.95 mm G550 steel up to -50 ℃, 1.0 mm G300 steel at -10 ℃ and all the G300 cold-rolled steel sheets at ambient temperature show that the ultimate strength is higher than the upper yield strength. Hence, the mechanical properties in these cases were obtained as per Figure 7 (a), while 0.2% proof stress was used as the yield strength for 0.95 mm G550 steel at ambient temperature and -10 ℃, which exhibited gradual yielding. However, the upper yield strength is higher than the ultimate strength in many other cases, in which case, the upper yield and ultimate strengths were obtained using the guidance in AS 1391 [9] and BS EN ISO 6892-1 [13], (Figure 7 (b)) while other mechanical properties were obtained as per Figure 7 (a).
The stress-strain curves of 0.55 mm G550 at all the temperatures, 0.75 mm G550 and all the tested G300 at -70 ℃ do not have either a yield plateau or strain hardening and thus do not match either Figure 7 (a) or (b). In these cases, the upper yield and ultimate strengths were obtained as per the guidance provided in AS 1391 [9] (Figure 7 (c)), while other mechanical properties were obtained as per Figure 7 (a). BS EN ISO 6892-1 [13] does not define the ultimate strength in this case and states that a separate agreement can be made with the parties concerned, if necessary. Also, ASTM A360-19 [14] does not provide a method to determine the mechanical properties in the cases similar to Figure 7 (b) or (c). However, the reduction rate of stress beyond upper yield strength is significantly less for 0.55 mm G550 in the temperature range of ambient temperature to -50 ℃.



a. Ultimate strength greater than upper yield strength.



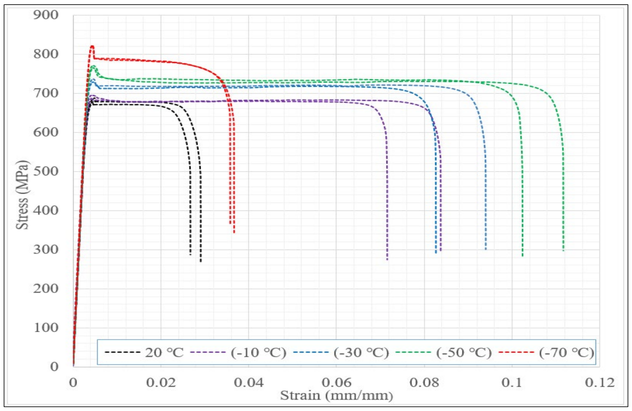
b. Ultimate strength less than upper yield strength.



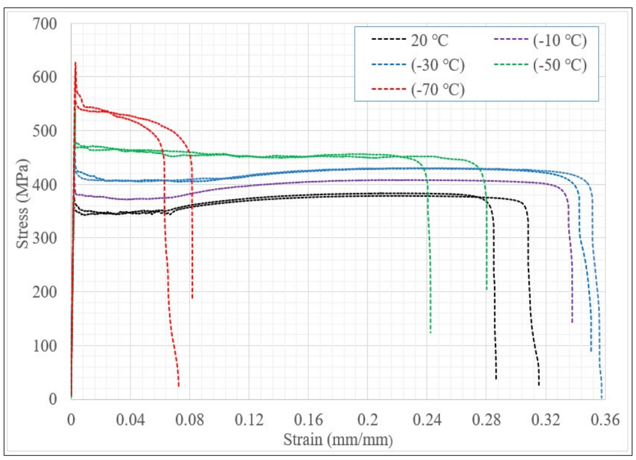
c. Ultimate strength less than upper yield strength, but without yield plateau or strain hardening.

Figure 7: Definitions of mechanical properties.

Figure 8 shows the stress-strain curves of 0.75 mm G550 and 0.8 mm G300 cold-rolled steel sheets. Stress-strain curves of 0.95 mm G550, 1.0 mm G300 and 0.55 mm G550 and G300 cold-rolled steel are reported in Rokilan and Mahendran [15].



a. G550 - 0.75 mm.



b. G300 - 0.8 mm.

Figure 8: Typical sub-zero temperature stress-strain curves of cold-rolled steel sheets.

3.1 Predictive equations

It is important to develop sub-zero temperature mechanical property predictive equations of cold-rolled steel sheets using their ambient temperature mechanical properties. This paper proposes suitable predictive equations for the sub-zero temperature mechanical property increment factors of yield strength, Young's modulus and ultimate strength in the temperature range of -70 ℃ to ambient temperature. The temperature dependent (T in ℃) increment factors are given as ratios of sub-zero temperature and ambient temperature mechanical properties. However, predictive equations are not proposed for ultimate and fracture strains as the sub-zero temperature strain to ambient temperature strain ratios do not show a regular pattern. Also, the ultimate and fracture strains depend on the steel grade and thickness.

Separate yield strength, upper yield strength and ultimate strength predictive equations are proposed for LSS and HSS as they show different incremental patterns. However, the same equation is given for LSS and HSS Young's modulus increment factors since differences are small. Importantly, the ambient temperature Young's modulus can be used at sub-zero temperatures since it increases only slightly with reducing temperature. Quadratic equations (1) are proposed except for the ultimate strength increment factor of LSS, for which a cubic equation (2) is proposed.

$$f_T/f_{20} = a \times 10^{-5}\, T^2 + b \times 10^{-3}\, T + c \qquad (1)$$

$$f_T/f_{20} = -1.8 \times 10^{-6}\, T^3 - 6.2 \times 10^{-5}\, T^2 - 1.8 \times 10^{-3}\, T + 1.075 \qquad (2)$$

where, T is temperature in ℃, a, b and c are coefficients in Table 1, f_T and f_{20} are the mechanical properties at sub-zero temperature T and ambient temperature, respectively.

Table 1: Coefficients a, b and c for Equations 1 and 2.

Mechanical property	Steel type	a	b	c
Yield strength	LSS	8	-3	1.028
	HSS	3	-1	1.008
Young's modulus	LSS & HSS	0.2	-0.5	1.009
Upper yield strength	LSS	7	-5.2	1.076
	HSS	2.6	-1.4	1.018
Ultimate strength	LSS	Refer to Equation 2		
	HSS	2	-1	1.012

Figures 9 to 12 show a good comparison between the proposed equations and test results and thus confirm the suitability of Equations 1 and 2 with their associated coefficients a, b and c in Table 1 in predicting the sub-zero temperature increment factors for yield strength, Young's modulus, upper yield strength and ultimate strength.

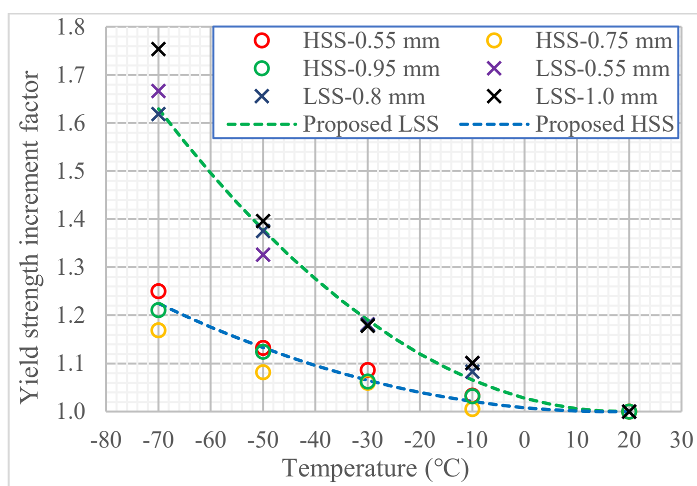


Figure 9: Comparison of experimental results with predictive equations for yield strength.

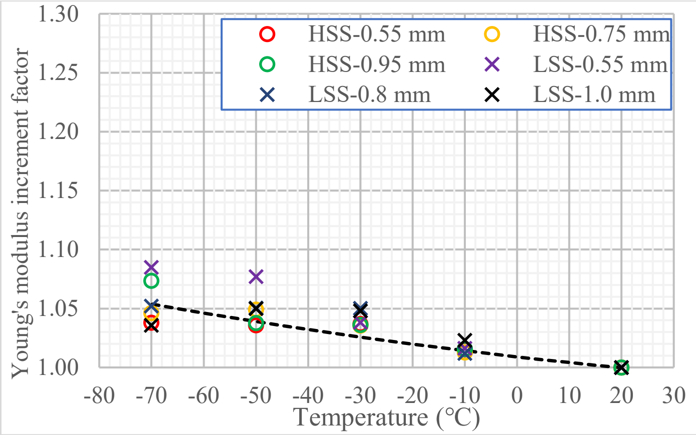


Figure 10: Comparison of experimental results with predictive equations for Young's modulus.

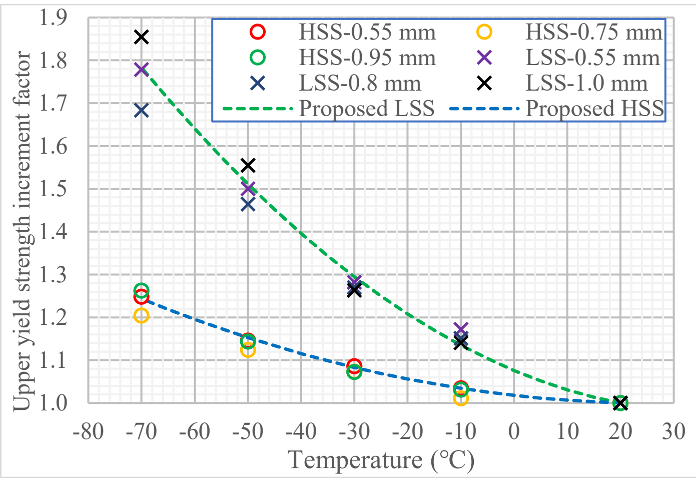


Figure 11: Comparison of experimental results with predictive equations for upper yield strength.

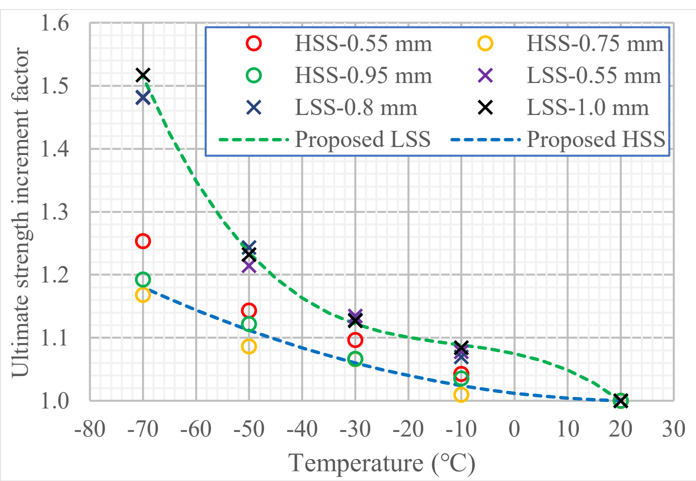


Figure 12: Comparison of experimental results with predictive equations for ultimate strength.

3.2 Ultimate and fracture strains

Ultimate strain is used to create a theoretical stress-strain curve while fracture strain is used to determine the ductility of steel. Also, Eurocode 3 Part 1.3 [16] uses the ratio of ultimate strain to yield strain as one of the parameters to define ductility. Ambient and sub-zero temperature ultimate and fracture strains of cold-rolled steel sheets are shown in Figures 13 and 14, respectively.

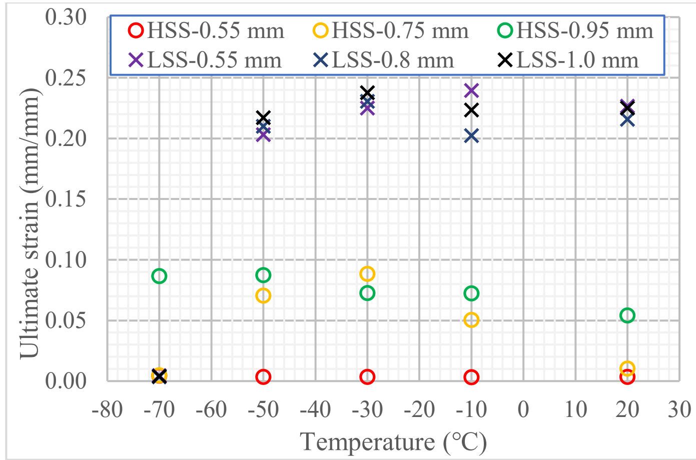


Figure 13: Ultimate strain of cold-rolled steel sheets.

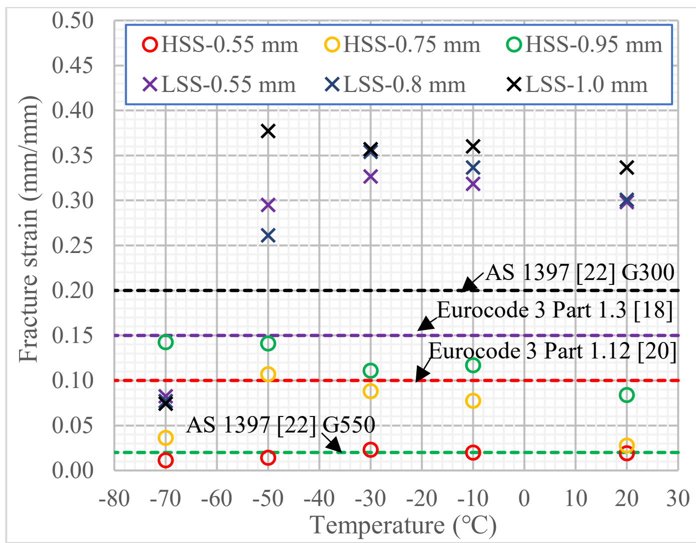


Figure 14: Fracture strain of cold-rolled steel sheets.

Fracture depends on both ductility and toughness. Ductility measures the ability to deform while toughness is the ability to absorb energy. Eurocode 3 Part 1.3 [16] gives three ductility requirements, ie. ultimate strength to yield strength $(f_u/f_{0.2})$ ratio, fracture strain (ε_f) and ultimate strain to yield strain $(\varepsilon_u/\varepsilon_y)$ ratio should be greater than 1.10, 15% and 15, respectively. However, Eurocode 3 Part 1.12 [17] reduces the ductility requirements for high strength steel (S460 to S700). It reduces the $f_u/f_{0.2}$ ratio to 1.05 and ε_f to 10% while keeping the $\varepsilon_u/\varepsilon_y$ ratio limit at 15. However, AS 1397 [18] gives more relaxed ductility requirements than Eurocode 3 Part 1.12 [17] for Australian CFS sections.

AS 1397 [18] gives the minimum fracture strains based on 50 mm gauge length for steels with thicknesses greater than 0.6 mm. Hence it cannot be used for both 0.55 mm G300 and G550 steels. But AS 1397 does not give any $f_u/f_{0.2}$ ratio limits. Figure 14 shows that HSS and LSS satisfy the minimum fracture strain requirement (2% for G550 and 20% for G300) in AS 1397 except for LSS at -70 ℃. However, LSS satisfy the minimum yield and ultimate strength requirements of G550 steel. Hence, it is questionable which minimum fracture strain is suitable. Fracture strains of LSS at -70 ℃ are greater than the requirement for G550 steel.

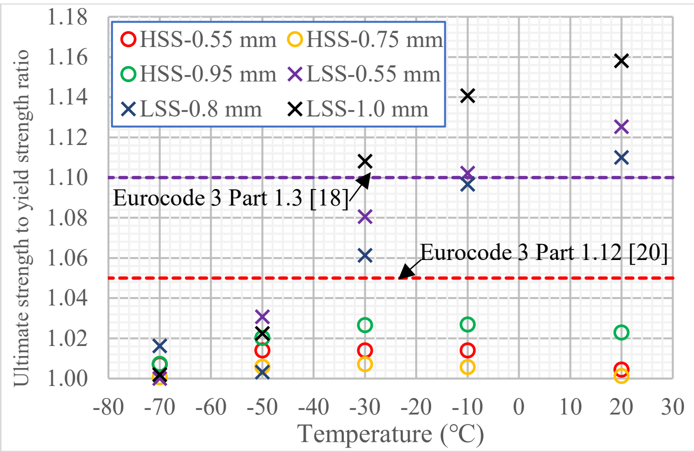


Figure 15: Ultimate strength to yield strength ratios.

LSS up to -50 ℃ satisfy the $(\varepsilon_u/\varepsilon_y)$ ratio and fracture strain requirements of Eurocode 3 Part 1.3 [16] (Figure 16). LSS at -70 ℃ do not even satisfy the Eurocode 3 Part 1.12 [17] fracture strain requirement although they satisfy the minimum yield and ultimate strength requirements of S460 steel. On the other hand, HSS (other than 0.55 mm G550) satisfy the $(\varepsilon_u/\varepsilon_y)$ ratio requirement of Eurocode 3 Part 1.12 [17] while only 0.95 mm HSS within the temperature range of -10 ℃ to -70 ℃ and 0.75 mm HSS at -50 ℃ satisfy the fracture strain requirement. None of the HSS satisfy the $f_u/f_{0.2}$ ratio requirement of Eurocode 3 Part 1.12 [17] while 1.0 mm LSS up to -30 ℃, 0.8 mm LSS at ambient temperature and 0.55 mm LSS up to -10 ℃ satisfy the $f_u/f_{0.2}$ ratio requirement of Eurocode 3 Part 1.3 [16]. Although LSS satisfy the $f_u/f_{0.2}$ ratio requirement of Eurocode 3 Part 1.12 up to -30 ℃, they do not satisfy the min. yield and ultimate strength requirements of S460 steel.

European steel design standards use the ratio of ultimate strength to yield strength $(f_u/f_{0.2})$ as one of the ambient and elevated temperature ductility parameters. As per this study, the $f_u/f_{0.2}$ ratio of LSS reduces with decreasing temperature while the fracture strain remains almost the same up to -50 ℃ (Figures 14 and 15). Also, the $f_u/f_{0.2}$ ratios of 0.75 mm and 0.95 mm HSS remain almost the same while the fracture strain increases up to -50 ℃. Therefore, it is questionable whether the ductility of cold-formed steel sections can be quantified by the ratio of $f_u/f_{0.2}$ at sub-zero temperatures. If the $f_u/f_{0.2}$ ratio requirement is not considered as one of the ductility requirements, LSS up to -50 ℃ and 0.95 mm HSS within the temperature range of -10 ℃ to -70 ℃ can satisfy the ductility requirements given in European steel standards [16, 17].

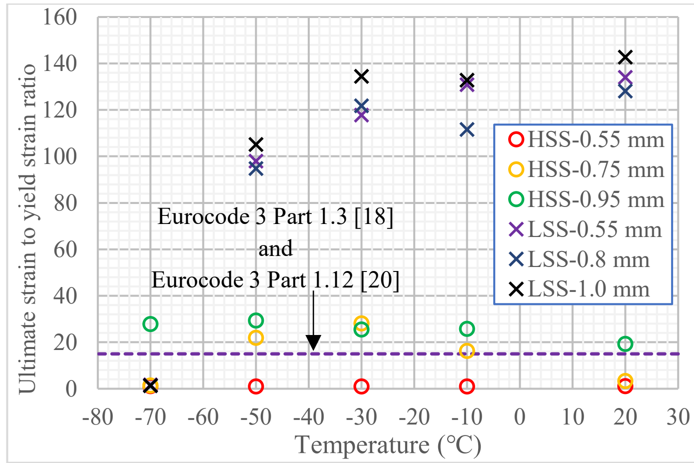
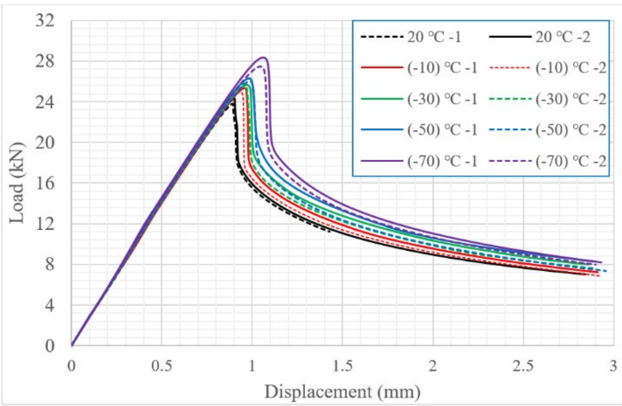


Figure 16: Ultimate strain to yield strain ratios.

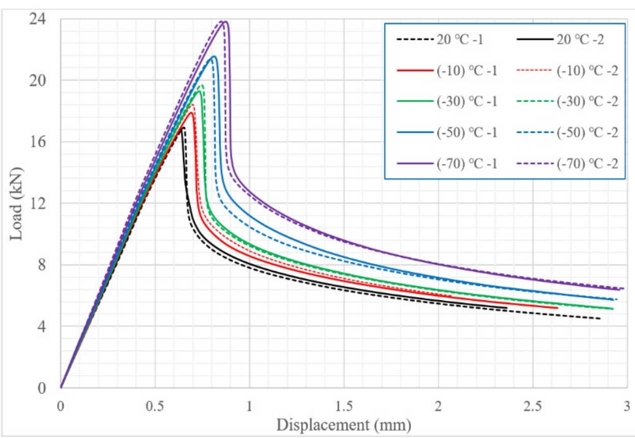
Although the sub-zero temperature fracture strains of both LSS and HSS (other than 0.55 mm) satisfy the minimum fracture strain in AS 1397 [18], it is essential to determine the toughness of cold-formed steel at sub-zero temperatures prior to arriving at a firm conclusion on the use of cold-formed steel sections in sub-zero temperature environment. Steel toughness can be determined by Charpy V-notch impact tests based on AS 1544.2 [19] or ASTM A360-19 [14] or BS EN 10045 Part 1 [20]. The recommended specimen width is 10 mm in all three standards, however, the recommended minimum thickness is 2.5 mm in the first two standards while it is 5 mm in the third standard. Hence, specific testing requirements must be provided in these standards to determine the toughness of thin cold-formed steels. On the other hand, AS/NZS 4600 [12] does not allow the use of its design methods if the structure is subject to brittle failures while AS 4100 [21] controls the use of steel at sub-zero temperatures based on the notch toughness characteristics of steel. However, as per AS 4100 [21] the allowed minimum negative temperature increases with reducing steel thickness. This implies the possibilities of using cold-formed steel sections at sub-zero temperatures as their thicknesses are small.

4. Column test results

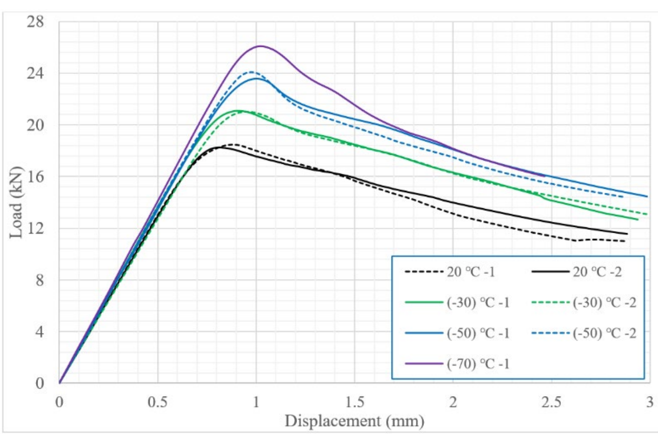
The ultimate capacities of tested LCS columns are given in Table 2 while their load versus displacement curves are shown in Figure 17. Typical stub column failures can be seen in Figure 6. Figure 14 shows very small fracture strains for 0.55 mm HSS. However column tests show that 0.55 HSS columns can be used up to -70 ℃ without a reduction in their ultimate capacity. Also, 0.55 mm and 0.8 mm LSS columns show significant increment in their capacity at sub-zero temperatures.



a. G550-0.55 mm.



b. G300-0.55 mm.



c. G300-0.8 mm.

Figure. 17. Load-displacement curves of tested columns.

There was no difference between the failure patterns of columns at ambient and sub-zero temperatures. The important observation is that no columns exhibited fracture failures. The failure patterns of 0.55 mm HSS columns at ambient and sub-zero temperatures are shown in Figure 18. Further details of column tests and results are given in [22].

Table 2. Ultimate capacities of tested LCS columns.

Temp. (℃)	Specimen number	G550 0.55 mm	G300 0.55 mm	G300 0.8 mm
20	1	23.80	16.93	18.47
	2	24.32	16.82	18.25
-10	1	25.34	17.89	-
	2	24.96	18.42	-
-30	1	25.64	19.28	21.08
	2	25.80	19.69	21.03
-50	1	26.29	21.55	23.57
	2	26.02	21.37	24.08
-70	1	28.34	23.81	26.09
	2	27.45	23.81	-

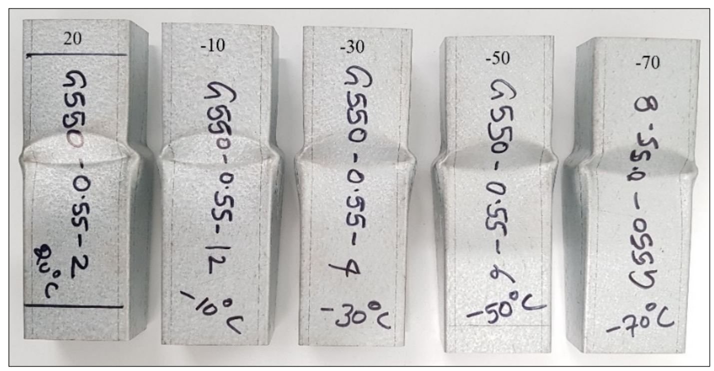


Figure 18: Failure patterns of 0.55 mm HSS columns

5. Conclusions

In this research, a detailed experimental study was conducted to determine the sub-zero temperature mechanical properties of low and high strength cold-rolled steel sheets. It also included an experimental investigation on the behaviour and capacities of low and high strength cold-formed steel columns subject to local buckling and yielding failures at sub-zero temperatures. The tensile coupon tests showed that yield strength, upper yield strength and ultimate strength of cold-rolled steel sheets increase with reducing temperature and that they satisfy the ductility requirements of AS/NZS 4600 [12] since they meet the fracture strain requirements in AS 1397 [18] except for LSS at -70 ℃ and 0.55 mm LSS and HSS. However, LSS satisfy the minimum yield and ultimate strength and fracture strain requirements of G550 steel at -70 ℃. New predictive equations are proposed to predict the sub-zero temperature (up to -70 ℃) mechanical properties such as yield strength, Young's modulus, upper yield strength and ultimate strength based on their ambient temperature mechanical properties.

Column tests have shown that 0.55 mm HSS and LSS CFS columns can be used up to -70 ℃ without any reduction to their ultimate capacity. Thus, the coupon tests and column tests indicate the possibility of using CFS as a structural material in sub-zero temperature environments. However, it is essential to determine the toughness of CFS at sub-zero temperatures before concluding that CFS can be used up to -70 ℃. Thus, future studies are needed by overcoming the current difficulties associated with the impact tests of CFS due to their small thicknesses.

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